Observation of the Decay $B_c^{\pm} \rightarrow J/\psi\,\pi^{\pm}$ and Measurement of the $B_c^{\pm}$ Mass

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The $B_c^\pm$ meson is observed through the decay $B_c^\pm \to J/\psi\,\pi^\pm$, in data corresponding to an integrated luminosity of 2.4 fb^{-1} recorded by the CDF II detector at the Fermilab Tevatron. A signal of 108 ± 15 candidates is observed, with a significance that exceeds $8\,\sigma$. The mass of the $B_c^\pm$ meson is measured to be 6275.6 $\pm$ 2.9 (stat.) $\pm$ 2.5 (syst.) MeV/c^2.

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The B_c^- meson [1] is composed of a bottom quark, b, and an anti-charm quark, $\overline{c}$, the heaviest quark flavors expected to form mesons. The presence of two relatively heavy quarks is unique in the $B_c^\pm$ system, and affects the theoretical calculation of the decay properties and mass of the $B_c^\pm$ meson. Either quark in the $B_c^\pm$ meson

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can decay weakly, which suggests copious decay modes [2] and an expected lifetime much shorter than that of other B mesons [3]. The mass of the $B_c^\pm$ meson has been predicted using a variety of theoretical techniques. Non-relativistic potential models have been used to predict a mass of the $B_c^\pm$ in the range of 6247 - 6286 MeV/c^2 [4], and a slightly higher value is found for a perturbative QCD calculation [5]. Recent lattice QCD calculations provide a $B_c^\pm$ mass prediction of $6304 \pm 12\ ^{+18}_{-0}$ MeV/c^2 [6]. Precision measurements of the properties of the $B_c^\pm$ are needed to test these calculations.

The $B_c^\pm$ meson is too massive to be produced at $e^+ e^-$ colliders operating near the $\Upsilon(4S)$ center of mass energy, and only a few candidate events, which were consistent with background processes, were observed at LEP [7]. With a large b-quark production cross section and powerful multipurpose detectors, the Fermilab Tevatron is well-suited to the study of all species of B hadrons, including the $B_c^\pm$ meson. In particular, this collaboration observed the $B_c^\pm$ meson in semileptonic decays and used these candidates to measure the lifetime of the $B_c^\pm$ to be $0.463^{+0.073}_{-0.065} \pm 0.036$ ps [8]. In addition, we have previously presented evidence for a $B_c^\pm \to J/\psi\, \pi^\pm$ signal [9].

In this Letter, an analysis is presented which observes the decay mode $B_c^\pm \to J/\psi\, \pi^\pm$, with $J/\psi \to \mu^+ \mu^-$, and precisely measures the $B_c^\pm$ mass. This result provides the first observation of the $B_c^\pm$ meson in a fully reconstructed mode. This observation is made in $p\overline{p}$ collisions at a center of mass energy of 1.96 TeV using the Collider Detector at Fermilab (CDF II) [10]. The results presented here are based on a data sample with an integrated luminosity of 2.4 fb^{-1}, and supercede our earlier measurement [9], which was based on an integrated luminosity of 360 pb^{-1}.

This analysis makes use of the tracking and muon identification systems. The tracking system consists of double-sided silicon detectors [11] and a 96 layer open-cell drift chamber (COT) [12] that operate inside a solenoid with a 1.4 T field oriented along the beam axis. Charged particles originating from the collision point are measured in the tracking system with a momentum resolution of $\sigma(p_T)/p_T \sim 0.0015\, p_T(\mathrm{GeV}/c)^{-1}$ [13]. Muon candidates from the decay $J/\psi \to \mu^+ \mu^-$ are identified by two sets of drift chambers located radially outside the electromagnetic and hadronic calorimeters. The central muon chambers cover the pseudorapidity region $|\eta| < 0.6$ and are sensitive to muons with transverse momentum $p_T > 1.4$ GeV/c. A second muon system covers the region $0.6 < |\eta| < 1.0$ and detects muons having $p_T > 2.0$ GeV/c. Muon triggering and identification are based on matching tracks measured in the muon system to COT tracks. This analysis is based on events recorded with a trigger that is dedicated to the collection of a $J/\psi \to \mu^+ \mu^-$ sample. The first level of the three-level trigger system requires two muon candidates with tracks in the COT and muon chamber systems that match in the transverse view. The second level imposes the requirement that muon candidates have opposite charge and limits the accepted range of opening angle between the two muon candidates. The highest level of the J/ψ trigger reconstructs the muon pair in software, and requires that the invariant mass of the pair falls within the range $2.7 - 4.0$ GeV/c^2.

The analysis of the data begins with a selection of well-measured $J/\psi \to \mu^+ \mu^-$ candidates. Events are required to contain two oppositely charged muon candidates that satisfy restrictive matching requirements, consistent with the full measurement precision of the COT and muon chamber systems. We also require that both muon tracks have associated measurements in at least three layers of the silicon detector and a two-track invariant mass within 70 MeV/c^2 of the world-average J/ψ mass [14]. This data sample provides approximately 17 million events containing J/ψ candidates, measured with an average mass resolution of 13 MeV/c^2.

Both $B^\pm \to J/\psi\, K^\pm$ and $B_c^\pm \to J/\psi\, \pi^\pm$ combinations are reconstructed in this analysis. The relatively plentiful $B^\pm$ sample serves as a reference signal and is used to develop criteria for the $B_c^\pm$ selection . These final states are identified by assigning the $\pi^\pm$ or $K^\pm$ mass to all tracks not used in the J/ψ reconstruction. In order to provide the measurement resolution sufficient to discriminate between directly produced tracks and B-hadron decay products, the $\pi^\pm$ and $K^\pm$ candidate tracks are required to have measurements on at least three layers of the silicon detector. Each three-track combination must satisfy a fit in which the tracks are required to originate from a common vertex and the invariant mass of the muon pair is constrained to the world average J/ψ mass. Approximately 65 000 $B^\pm$ candidates are identified in this loosely selected sample.

The selection requirements are further improved to give a large $B^\pm \to J/\psi\, K^\pm$ signal with very small background, in order to increase the significance of the $B_c^\pm$ observation. Since the $B_c^\pm$ lifetime is significantly shorter than the lifetime of the $B^\pm$, each selection variable under consideration has been studied for its effect on preserving signal and removing background only for $J/\psi\, K^\pm$ combinations with $80 < ct < 300\,\mu$m, where t is the proper decay time determined from $t \equiv \vec{L_T} \cdot \vec{p_T}(B) \frac{M(B)}{|p_T(B)|^2}$, $M(B)$ is the mass of the combination, $\vec{p_T}(B)$ is the transverse momentum of the combination, and $\vec{L_T}$ is the transverse displacement of the $J/\psi\, K^\pm$ decay vertex from the beamline. Each selection quantity considered is evaluated for its efficiency in retaining the $B^\pm$ signal and reducing the combinatorial background in the $5.4 - 5.5$ GeV/c^2 mass range.

Several characteristics of the $J/\psi\, K^\pm$ candidates are considered for selection requirements. Minimum p_T requirements on the $K^\pm$ and $B^\pm$ candidates are used to suppress backgrounds from $J/\psi\, K^\pm$ combinations that are not related to the $B^\pm$ decay. Reasonable vertex quality is assured by placing a minimum value on the accepted probability $P(\chi^2)$ of the mass- and vertex-constrained fit used to obtain the $B^\pm$ candidate. The trajectory of the $K^\pm$ is required to originate from the $B^\pm$ decay ver-

tex by placing a requirement on its distance of closest approach $d_{SV}(K)$ and associated uncertainty $\sigma_{d_{SV}}(K)$ with respect to the vertex found in the J/ψ fit. Similar quantities $d_{PV}(K)$ and $\sigma_{d_{PV}}(K)$ measured with respect to the primary vertex are used to remove tracks that originate from direct production processes. We suppress the promptly-produced combinatorial background by rejecting candidates with small ct. A requirement on σ_{ct} removes poorly-reconstructed combinations and other backgrounds. We also reject $J/\psi\, K^{\pm}$ combinations that are inconsistent with having originated from the beamline by requiring a small magnitude for the transverse impact of the candidate, $\vec{d}_{PV}(B) \equiv \vec{L_T} \times \vec{p_T}(B)/|p_T(B)|$, and a small angle β between $\vec{L_T}$ and $\vec{p_T}(B)$.

Two sets of selection criteria based on these quantities are listed in Table I. The first step of the selection process is to impose the "standard" selection requirements listed above and retain all $J/\psi\, K^{\pm}$ combinations that satisfy them. However, the selection studies indicate that a substantial number of $B^{\pm} \to J/\psi\, K^{\pm}$ signal events fail exactly one of the standard selection requirements. To increase the overall signal efficiency, we introduce a "high-p_T" selection, comprised of combinations that satisfy more restrictive p_T requirements, and pass all but one of the other high-p_T selection criteria in Table I. Figure 1 shows the reconstructed $B^{\pm} \to J/\psi\, K^{\pm}$ signal for candidates that satisfy the standard or high-p_T selection criteria. The additional combinations retained by the high-p_T selection increase the $B^{\pm}$ yield by 28%. The total signal of approximately 21 100 $B^{\pm}$ candidates with a small background of 430 events in the $B^{\pm}$ sideband region between 5.4 and 5.5 GeV/c^2 demonstrates that this selection effectively removes the background to B-hadron candidates.

TABLE I: Selection variables and requirements for the standard selection and high-p_T selection as described in the text. Here "Trk" refers to the track combined with the J/ψ and may be a $K^{\pm}$ or $\pi^{\pm}$ candidate for the $B^{\pm}$ or $B_c^{\pm}$ respectively.

Selection variable	Standard	High-p_T
$p_T(Trk)$	> 1.7 GeV/c	> 2.5 GeV/c
$p_T(J/\psi\ Trk)$	> 5 GeV/c	> 6 GeV/c
$P(\chi^2)$	$> 0.1\%$	$> 1\%$
$\lvert d_{SV}(Trk)\rvert$	$< 100\ \mu$m	$< 80\ \mu$m
$\lvert d_{PV}(Trk)\rvert/\sigma_{d_{PV}(Trk)}$	> 2.5	> 3
$\lvert d_{PV}(B)\rvert/\sigma_{d_{PV}(B)}$	< 2.5	< 2
ct	$> 80\ \mu$m	$> 100\ \mu$m
σ_{ct}	$< 30\ \mu$m	$< 25\ \mu$m
β	< 0.4 radians	< 0.3 radians

The candidates used for the reconstruction of the $B_c^{\pm}$ are obtained by applying the selection criteria in Table I to the sample interpreted as $J/\psi\, \pi^{\pm}$. Figure 2 shows the $B_c^{\pm} \to J/\psi\, \pi^{\pm}$ candidates under the combined standard and high-p_T selections. The data are also shown for a limited mass region suggested by theoretical expectations [4, 5, 6]. A clear excess of $J/\psi\, \pi^{\pm}$ combinations is evident around 6280 MeV/c^2.

The data shown in Fig. 2(b) are fitted using an unbinned log likelihood function that uses a Gaussian shape for the signal plus a background model that includes contributions from both combinatorial sources and contributions from Cabibbo-suppressed $B_c^{\pm} \to J/\psi\, K^{\pm}$ decays in the probability distribution function. Simulated events are used to estimate the mass distribution expected from the misidentified Cabibbo-suppressed process, and it is found to be approximately Gaussian, centered 60 MeV/c^2 below the true $B_c^{\pm}$ mass and having a 30 MeV/c^2 width. The characteristic width for the signal in the probability distribution function is varied for each candidate in proportion to the mass uncertainty estimated from the individual track uncertainties. A similar fit performed on the $B^{\pm}$ candidates finds that the mass resolution is underestimated by a factor of 1.55 with this method. Consequently, the mass uncertainties used in the $J/\psi\, \pi^{\pm}$ fit are scaled by this factor. For the central value of the fit, the Cabibbo-suppressed contribution is fixed to 0.05 of the total $B_c^{\pm}$ yield, which is comparable to the measurements obtained for Cabibbo-suppressed $B^{\pm}$ decays [14]. Fig. 2(b) shows a projection of the fit overlaid on the data, which has $\chi^2/DoF = 34.6/32$ and a probability of $P(\chi^2) = 0.30$.

The result of the unbinned fit over the mass range $6150 - 6500$ MeV/c^2 gives a $B_c^{\pm}$ signal of 108 ± 15 candidates with a mass of 6275.6 ± 2.9 MeV/c^2. This fit was repeated over the same mass range with the constraint that no signal is present in order to obtain a significance measurement. The ratio of likelihoods between the two fits yields a probability for the null hypothesis of 1.2×10^{-16}, equivalent to a fluctuation of 8σ or more in a Gaussian distribution. A second significance test was also performed, which used a Monte Carlo simulation to estimate the probability for a background-only sample to mimic a signal at least as significant as the one observed. This study confirmed the significance estimate obtained from ratio-of-likelihoods test. We conclude that this enhancement is an observation of the process $B_c^{\pm} \to J/\psi\, \pi^{\pm}$.

Studies that were performed for the mass measurement of other B mesons that contain a J/ψ in the final state [15] are used for an evaluation of some of the systematic uncertainties. The systematic uncertainty due to tracking detector misalignments and material distributions used in track fitting is assessed by varying these within reasonable limits. Based on these studies, a systematic uncertainty of 0.6 MeV/c^2 is assigned to account for misalignments and material modeling. A comparison between the fitted $B^{\pm}$ mass in 12 independent periods of data finds the measured mass of the $B^{\pm}$ meson for each subset to be within 1.8σ of the entire sample. Consequently, no systematic uncertainty is assigned for time dependent effects on this mass measurement. The momentum scale of the tracking system is calibrated with

the J/ψ, $\psi(2S)$, and Υ states, all of which have been well measured previously [14]. The uncertainty of the momentum scale for the decay products of $B_c^{\pm}$ which was derived from this calibration contributes an additional mass uncertainty of 0.6 MeV/c^2. The sensitivity of the mass measurement to the assumed Cabibbo-suppressed background process was tested with simulated events. Variations of $0.0 - 0.1$ for the fractional contribution correspond to mass measurement variations of 0.8 MeV/c^2, which is taken to be the systematic uncertainty associated with this unknown background contribution.

An additional systematic uncertainty comes from the fitting procedure. The scale factor associated with the mass uncertainty which is used in the fit was set to the best value obtained in a fit to the topologically similar $B^{\pm} \to J/\psi\, K^{\pm}$ final state. However, other reconstructed B hadrons that include a J/ψ in the final state have been studied as well. Scale factors in the range of 1.25 - 2.0 have been suggested by these studies, so the fit for the $B_c^{\pm}$ mass was repeated for this range. An uncertainty of 2.2 MeV/c^2 in the calculated $B_c^{\pm}$ mass is indicated due to the fitting procedure. The combined systematic uncertainty is the sum in quadrature of the uncertainties in our calibration, tracking, and fitting procedure. The total systematic uncertainty in the $B_c^{\pm}$ mass measurement is determined to be 2.5 MeV/c^2.

In conclusion, we have observed fully reconstructed $B_c^{\pm}$ mesons through the decay $B_c^{\pm} \to J/\psi\,\pi^{\pm}$. A signal of 108 ± 15 candidates is observed with a significance greater than an 8σ fluctuation of a Gaussian distribution. The mass of the $B_c^{\pm}$ meson is measured to be $6275.6 \pm 2.9(\text{stat.}) \pm 2.5(\text{syst.})$ MeV/c^2.

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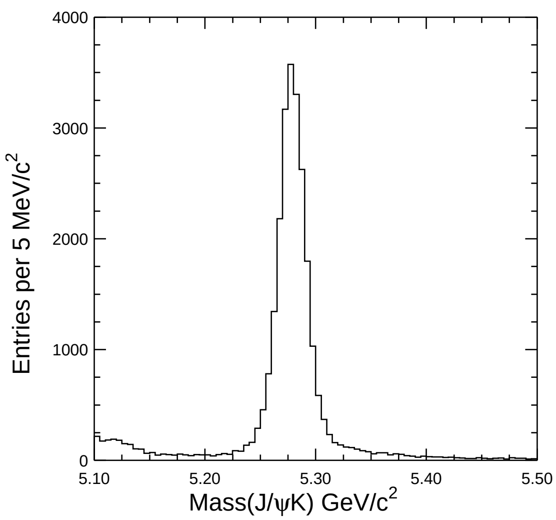

FIG. 1: The invariant mass distribution of $J/\psi\, K^{\pm}$ combinations.

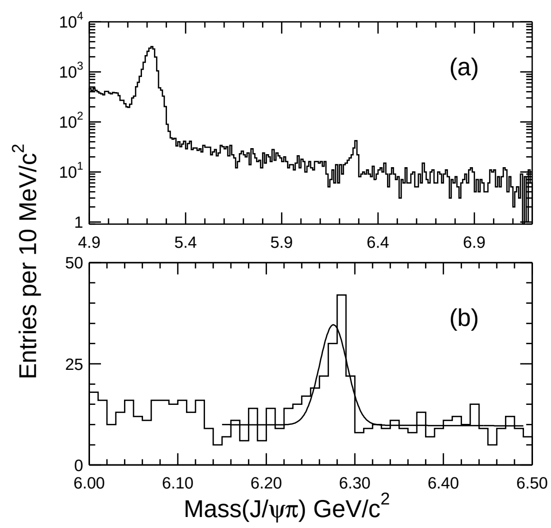

FIG. 2: (a). The invariant mass distribution of $J/\psi\, \pi^{\pm}$ combinations. (b) Identical to (a), but in a narrower mass range around the theoretically favored $B_c^{\pm}$ mass. The projection of the fit to the data is indicated by the curve overlaid on (b).